Assess Your Plant's True Water-Savings Potential

Using the minimum water network involves detailed analysis of plant configuration and design, material and energy balances, design and thermodynamic constraints

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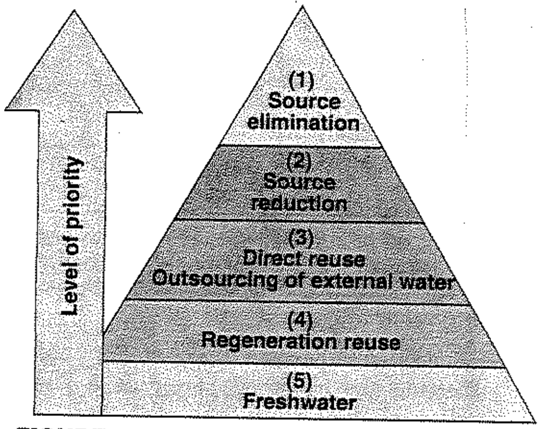

FIGURE 1. The water management hierarchy

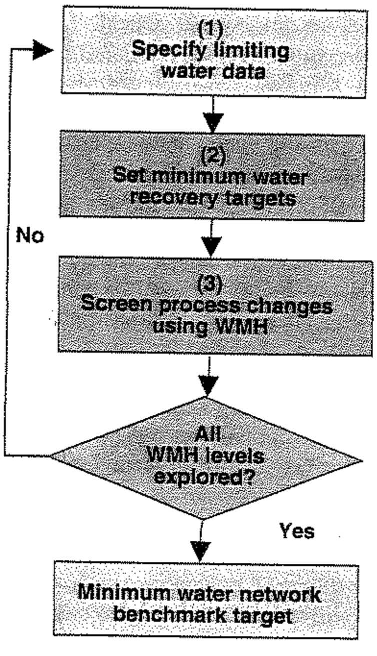

FIGURE 2. A holistic framework for establishing the MWN benchmark target

For companies in the chemical process industries, water is an indispensable utility. But the growing scarcity of quality industrial water, combined with stricter environmental regulations and the rising cost of wastewater treatment, have encouraged the conservation of water as a key utility in process plants. Concurrently, the development of systematic techniques for water reduction has made significant progress.

Many companies employ a combination of intercompany and intracompany benchmarking techniques to set realistic utility savings targets. In the former, companies reference the achievements of other companies in the same business, while in the latter, they refer to their own past performance. Intercompany and intracompany benchmarkings are usually part of a company's total quality management program, which calls for the relevant department to set annual targets for continuous improvement.

To meet these quality management requirements, a conservative utility savings target of, for example, 5% per year is typically specified. This target is set quite apart from considerations of the technical potentials and limitations, design and thermodynamic constraints of a plant. Hence, the true potential of a plant can be missed.

The advent of water-pinch analysis (WPA) as a tool for the design of a maximum-water-recovery (MWR) network enables a process plant to both assess its inherent potential for saving utilities and benchmark its performance based on the structure, operating conditions, design and thermodynamic characteristics that are unique to the plant. Since its introduction by Wang and Smith [*1*], various noteworthy WPA developments on targeting, design, optimization and improvement of an MWR network have emerged. These include works on processes with fixed flowrate and fixed concentration [*2, 3, 4, 5*], regeneration targeting [*6, 7*], numerical water targeting [*5*], network design to achieve water targets [*1, 9, 10, 7, 4, 11*], mathematical modeling, network superstructure optimization and problems with multiple contaminants [*8, 12–19*], water network retrofit [*20*], water targeting for batch systems [*21–23*] and capital-cost targeting and optimization [*24, 20*].

Wan Alwi and others [*25*] recently made the first attempt to implement WPA on urban systems by using their water-cascade-analysis (WCA) technique to establish water targets and design an MWR network for a mosque. Liu and others provide comprehensive practical steps for conducting water-minimization project focusing on maximizing spent water reuse [*26*]. Most authors of the aforementioned projects claim that their methods lead to

A CASE STUDY: SETTING TARGETS FOR MINIMUM WATER NETWORK IN A SEMICONDUCTOR FABRICATION PLANT

Water is a major utility for many sectors of the chemical process industries, but for semiconductor manufacturers, it is also a precious commodity. The extreme water demands of a semiconductor fabrication plant — from the ultrapure water required for chipmaking processes to potable water and, increasingly, recycled water for plant operations and maintenance — provide an ideal case study for the application of MWN benchmarking techniques.

In this case, the facility is MySem, a semiconductor fabrication plan in Malaysia. While the facility's primary activity is research and development (R&D), it produces 6-in. and 8-in. wafers. **Figures 3** and **4** show the plant's water distribution network. Water demands include ultrapure deionized (DI) process water for solvent processes, acid processes, wet cleaning and tools cleaning; the rest is for plant operations such as abatement, scrubber, cooling tower and wet bench cooling, and maintenance such as toilet flushing, office cleaning, wash basin, toilet pipes and ablution, as summarized in **Figure 5**.

Total water consumption varied throughout the year, depending on wafer production and equipment conditions. During the month of the benchmarking study, the plant's estimated total freshwater consumption was 42.6 m^3/h. Of this value, 31.78 m^3/h was used for DI water production and the rest for plant operations and maintenance.

Step 1. Specify the limiting water data

This step involved detailed process survey and line tracing, establishing process stream material balances and conducting water quality tests. Stream flowrates were extracted from data collected by either the plant's distributed control system (DCS) or ultrasonic flowmeters. Depending on the stream audited, tests for total suspended solids (TSS), biological oxygen demand (BOD), chemical oxygen demand (COD), total dissolved solids (TDS) were conducted onsite. For processes that only used ultrapure water, TSS levels were negligible. BOD was absent since no biological contaminants were present. COD was a component of TDS. TDS was ultimately chosen as the dominant water-quality parameter. TDS was monitored using a conductivity meter. Some of the key constraints considered included the following:

- Water streams with hydrogen fluoride (HF), isopropyl butanol (IPA) and dangerous solvents were not considered as water source
- Multimedia filter (MMF) backwash was not considered as water source since it contained high TSS
- WB202 and 203 cooling were not reused since they involved acid spillage
- Black water from toilets and toilet piping and office cleaning wastewater were not reused
- Greywater could only be reused for processes that did not involve body contact

For comparison and analysis of limiting water data, the relevant water streams having potential for recycling were compiled according to process sources and demand. **Table 1** shows the water sources and demands extracted for the plant in terms of flowrate and contaminant concentration. ,

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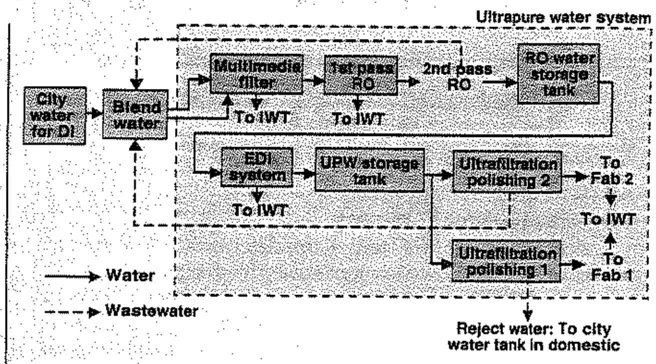

FIGURE 3. Process flow diagram for the ultrapure water system

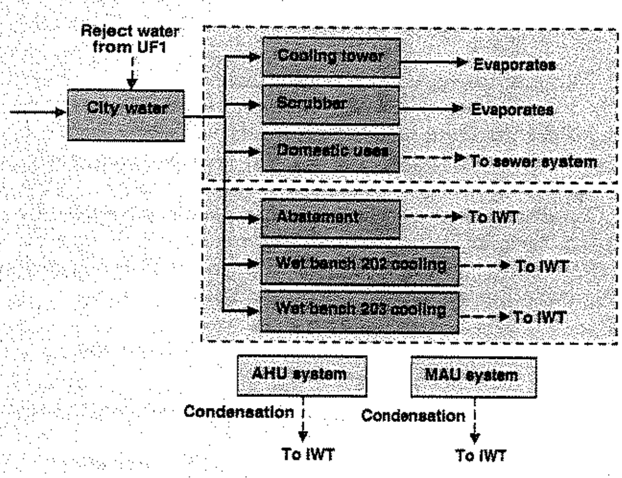

FIGURE 4. Water uses for plant operations and maintenance

TABLE 1. LIMITING WATER DATA

	Demand	F, m^3/h	C[1], ppm		Source	F, m^3/h	C, ppm
D1	MMF inlet	32.0	52	S1	MMF rinse	1.33	48.0
D2	Cooling tower	6.00	100	S2	RO reject 1st pass	9.80	70.4
D3	Abatement	2.73	100	S3	EDI reject	3.36	48.6
D4	Scrubber	0.54	100	S4	WB101 rinse water, idle	0.38	0
D5	Toilet flushing	0.08	100	S5	WB101 rinse water, operation	0.07	4,608
D6	Wash basin	0.01	52	S6	WB102 rinse water, idle	0.22	0
D7	Ablution	0.15	52	S7	WB102 rinse water, operation	0.07	4,480
D8	Toilet pipes	0.12	52	S8	WB201 rinse water, idle	0.76	0
D9	Office cleaning	0.05	52	S9	WB201 rinse water, operation	0.03	23,360
D10	MMF backwash	2.08	52	S10	WB202 rinse water, idle	3.48	0
D11	MMF rinse	1.33	52	S11	WB202 rinse water, operation	0.07	163.2
D12	WB203 cooling	1.47	52	S12	WB203 rinse water, idle	3.63	0
D13	WB202 cooling	1.22	52	S13	WB203 rinse water, operation	0.28	928
Total water demands		47.78	m^3/h	S14	MAU	1.11	6.4
				S15	AHU	0.36	11.5
				S16	Cassette cleaner	0.08	0
				S17	Abatement	2.73	105.6
				S18	Wafer scrubber	0.54	12.8
				S19	RO reject 2nd pass	4.50	19.2
				S20	UF1 reject	1.54	19.2
				S21	UF2 reject	1.80	0
				S22	Heater WB101	0.46	0
				S23	Wash basin	0.01	60
				S24	Ablution	0.15	40
				Total water sources		36.76	m^3/h

1. C is total dissolved solvents.

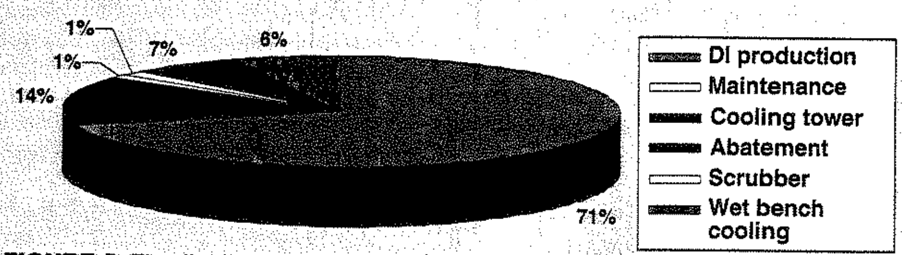

FIGURE 5. The distribution of freshwater

SEMICONDUCTOR PLANT CASE STUDY (continued)

Step 2. Establish targets for maximum water recovery

In this step, base-case MWR targets are determined. A water cascade table (WCT) of the plant that shows freshwater and wastewater flowrate targets at F_{FW}=11.04 m^3/h and F_{IWT}=0.019m^3/h, respectively, as shown in **Table 2.** Note in **Table 2** the cleanest water targeted water at 0 ppm concentration actually refers to DI water (F_{DI}) needed to be supplied to the blend water tank instead of freshwater. The reason is that the plant's freshwater had a concentration of 30 ppm. The source water flowrate at 30 ppm shown in **Table 2** *was actually the amount of freshwater supply needed.* As computed by WCA, F_{DI} = 0 m^3/h and F_{FW} = 11.04 m^3/h. The F_{IWT} of 0.02 m^3/h shown in **Table 2** consists only of the IWT wastewater that was considered for reuse. The total IWT should also include 5.69 m^3/h IWT wastewater that is not available for reuse due to chemical contamination, giving a total IWT of 5.71 m^3/h to be discharged, as shown in **Table 3.** Considering the present integration schemes implemented by the fab, the initial FW and total IWT flowrates were 39.94 m^3/h and 34.45 m^3/h, respectively. Equations 1 and 2 (**Table 3**) gave FW and IWT reductions of 72.4% and 83.4% respectively.

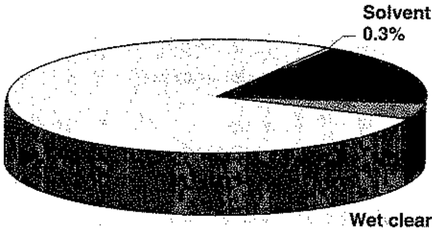

FIGURE 6. Water applications at semiconductor fabrication plant

TABLE 2. BASE-CASE MAXIMUM WATER RECOVERY TARGETS FOR SEMICONDUCTOR FAB (WITHOUT PROCESS CHANGES)

C, ppm	Purity, P	ΔP	Sum F demand, m^3/h	Sum F source, m^3/h	Total F, m^3/h	Cum water flowrate, m^3/h	Water surplus, m^3/h	Cum water surplus, m^3/h
						F^{DI} = 0		
0	1			10.808	10.808			
		0.000006				10.808	6.92E-05	
6.4	0.999994			1.11	1.11			6.92E-05
		0.000005				11.918	6.1E-05	
11.52	0.999988			0.36	0.36			0.00013
		0.000001				12.278	1.57E-05	
12.8	0.999987			0.54	0.54			0.000146
		0.000006				12.818	8.2E-05	
19.2	0.999981			6.04	6.04			0.000228
		0.000011				18.858	0.000204	
30	0.99997			F^{FW}= 11.04	11.04			0.000432
		0.00001				29.898	0.000299	
40	0.99996			0.15	0.15			0.000731
		0.000008				30.048	0.00024	
48	0.999952			1.33	1.33			0.000971
		0.000001				31.378	2.01E-05	
48.64	0.999951			3.36	3.36			0.000991
		0.000003				34.738	0.000117	
52	0.999948		–38.43	0	-38.43			0.001108
		0.000008				–3.692	–3E-05	
60	0.99994			0.01	0.01			0.001078
		0.00001				–3.682	–3.8E-05	
70.4	0.99993			9.8	9.8			0.00104
		0.00003				6.118	0.000181	
100	0.9999		–9.35		-9.35			0.001221
		0.000006				–3.232	1.8E-05	
105.6	0.999894			2.73	2.73			0.001203
		0.000058				–0.502	–2.9E-05	
164	0.999836			0.069	0.069			0.001174
		0.000764				–0.433	–0.00033	
928	0.999072			0.278	0.278			0.000843
		0.003552				–0.155	–0.00055	
4,480	0.99552			0.069	0.069			0.000292
		0.000128				–0.086	–1.1E-05	
4,608	0.995392			0.071	0.071			0.000281
		0.018752				–0.015	–0.00028	
23,360	0.97664			0.034	0.034			0 (pinch)
		0.97664				F^{IWT} = 0.019	0.018558	
								0.018558

the minimum freshwater and wastewater targets.

MWR which relates to maximum reuse, recycling and regeneration has two limitations. First, it only partly addresses the water-minimization problem since crucial water-minimization options such as elimination and reduction are neglected. Second, since MWR focuses on water reuse and regeneration, strictly speaking, it does not lead to the *minimum-water targets* as widely claimed by some researchers over the years.

A new procedure to establish the minimum utility targets relates to the maximum potential utility savings for a manufacturing plant. The focus is on setting the best achievable, or the minimum water and wastewater benchmark targets for a plant using the minimum water network (MWN) technique [*28*]. The procedure involves detailed analysis of a plant configuration and design, material and energy balances, design and thermodynamic constraints. The MWN technique strives to achieve maximum water reduction, and hence, maximum savings holistically after considering not only reuse and recycling, but all conceivable options to reduce water usage through elimination, reduction, reuse, outsourcing and regeneration. The true water-saving potential of a plant can be realized by the application of the MWN technique, in this case, for example, in a semiconductor fabrication plant

BENCHMARKS FOR THE MINIMUM WATER NETWORK

MWN is a holistic framework for water management. A key feature of this holistic framework is the water-management hierarchy (WMH), which provides a guide for prioritizing process changes qualitatively as well as quantitatively. The WMH consists of five levels:

- Source elimination
- Source reduction
- Direct reuse and outsourcing of external water
- Regeneration
- Freshwater consumption

The levels are arranged in order of preference, with the most preferred option at the top of the hierarchy (Level 1) to the least preferred at the bottom (Level 5) as in **Figure 1** [*29*]. Water minimization is concerned with the first to the fourth level of the hierarchy. The key steps to establishing MWN benchmark targets are illustrated in **Figure 2** and are described next.

Step 1. Specify limiting water data

The first step is to specify the limiting water data. This step employs process line-tracing, establishes process mate-

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TABLE 3. AMOUNT OF IWT AND DOMESTIC WASTEWATER NOT USED AND USED INITIALLY FOR INTEGRATION

Utility	Before MWR (m^3/h)	After MWR (m^3/h)	% reduction
Total freshwater	39.94	11.04	72.4
Total IWT wastewater	34.45	5.71	83.4
Total domestic WW	0.41	0.25	39.0

$$\text{FW savings, \%} = \frac{\text{FW flowrate before MWN} - \text{FW flowrate targets after MWN}}{\text{FW flowrate before MWN}} \times 100 \quad (1)$$

$$\text{IWT savings, \%} = \frac{\text{IWT flowrate before MWN} - \text{Total IWT to be discharged}}{\text{IWT flowrate before MWN}} \times 100 \quad (2)$$

TABLE 4. VARIOUS PROCESS CHANGES OPTIONS APPLICABLE FOR THE PLANT

WMH	Strategy	Option selected based on NAS	Option selected based on MWN procedure
Elimination	Abatement : Option 2 (decommisioning)	×	×
	WB 202 and 203 cooling	✓	✓
Reduction	WB reduction in Fab 1 and 2	✓	✓
	Heater reduction	✓	✓
	Fab 1 return reduction	✓	✓
	Abatement		
	: Option 1 (0.5gpm during idle)	×	×
	: Option 3 (recirculation)	✓	×
	: Option 4 (on demand)	×	✓
	: Option 5 (pH analysis)	×	×
	Increase RO system recovery/ install 3rd stage	✓	✓
	EDI return reduction		
	: Option 1 (decommissioning)	×	×
	: Option 2 (run intermittent)	✓	✓
	Domestic reduction	✓	×
	Cooling tower reduction using N2	✓	✓
	MMF reduction by NTU analysis	✓	✓
Reuse	Total reuse	✓	✓
Outsourcing	RW harvesting	✓	✓
Regeneration	Treat all WB water	×	✓

(✓) for selected option. (×) for eliminated option by MySem

After calculating the base-case MWR targets, all potential process changes to improve the fab's water system were listed according to the various WMH levels, as shown in **Table 4**. Central to the MWN approach is the level-wise hierarchical screening and prioritization of process change options using the water management hierarchy (WMH), and three new option-screening heuristics, which was sequentially applied to priorities process changes. Initially, the fab selected process changes based on the net annual savings (NAS) associated with each process change, as shown with check marks in column 3 of **Table 4**. The ultimate minimum water targets obtained after MWN analysis were given check marks in column 4 of **Table 4**. The steps for screening the options according to the WMH are described next.

Source elimination. The pinch point obtained from the base-case MWR targeting stage was 23,360 ppm (See **Table 2**). To maximize freshwater savings, the top priority was to consider eliminating water demands above the pinch point in the cascade table, or any demand with a concentration less than 23,360 ppm. All the water demands in **Table 1** met this criterion. All possible means to change

TABLE 5. VARIOUS EFFECTS OF EDI OPTIONS ON WATER TARGETS

EDI system	FW target, m^3/h	IWT target, m^3/h
Initial EDI flow rate	6.6094	0.0354
Option 1(decommission 3 EDI unit)	6.3038	0.0378
Option 2(run intermittently)	6.9281	0.0351

TABLE 6. EFFECT OF ABATEMENT OPTIONS ON WATER TARGETS

Abatement system	FD, m^3/h	FS, m^3/h	FW target, m^3/h	IWT target, m^3/h
Initial abatement flow rate	2.73	2.73	6.0857	0.0387
Option 1(0.5gpm during idle)	1.11	1.11	6.0837	0.0367
Option 2(decommissioning)	1.36	1.36	6.0840	0.0370
Option 3(recirculation)	0.14	0.00	6.2183	0.0333
Option 4(on demand)	0.57	0.57	6.0831	0.0361
Option 5(pH analysis)	0.79	0.79	6.0833	0.0363

the process, or the existing equipment to new equipment to eliminate water demands were considered. From Table 4, it was possible to eliminate D12 and D13 by replacing the wet-bench 202 and 203 quartz tanks, which initially needed continuous water for cooling, with PTFE tanks. Not only did this option eliminate the water requirement, it also eliminated the risk of tank cracks due to sudden temperature drops. Elimination of D12 and D13 resulted in new water targets of 8.3525 m^3/h for freshwater and 0.0215 m^3/h for wastewater (See third row, **Figure 7**). The pinch point was maintained at 23,360 ppm.

Source reduction. After eliminating D12 and D13, the next process change considered according to WMH was to reduce demands above the pinch point in the cascade table; i.e. any demand with concentration lower than 23,360 ppm. **Table 4** lists a few process-change options related to source reduction. Following Heuristic 2, the demand at the lowest contaminant concentration (52 ppm) was reduced first. Following are possible source reduction process changes (listed in **Table 4**) affecting demands D1, D10 and D11 (all located at 52 ppm) and sources S1 to S13 and S19 to S22 simultaneously due to the interactions between equipment in the water system of the DI plant (**Figure 3**):

- Wet-bench flowrate reduction to the minimum during idle mode
- Recirculating hot water and switching heater on demand for heater WB201
- Reduction of Plant 1 return flowrate by changing to variable speed pump
- Decommissioning three EDI units instead of running four units. Note that a sharp decrease in flowrate due to upstream process changes made it possible to reduce three EDI units (Option 2 from **Table 4** was rejected due to the increase in FW and IWT targets. Option 1, i.e decommissioning three EDI units, reduced the FW and IWT targets to 6.3038 m^3/h and 0.0378 m^3/h respectively (**Table 5**) and was hence implemented)
- Increase rate of recovery for reverse osmosis system
- Decrease multimedia filter backwash and rinsing time

Using Heuristic 1, the source reduction process changes for the DI water system shown in **Figure 3** were implemented from the core of the process (wet bench systems) to the most outer layer (multimedia filter). Excessive water usage at the core of the system was the main reason for water wastage at the outer layers. Hence, improving the core of the system first will reduce wastage downstream. Implementation of the entire range of process changes, from wet bench to MMF, listed in **Table 3**, gave revised freshwater and wastewater targets at 6.0857 m^3/h and 0.0387 m^3/h and a new pinch concentration at 4,608 ppm.

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SEMICONDUCTOR PLANT CASE STUDY (continued)

TABLE 7. WATER TARGETS AFTER IMPLEMENTATION OF MWN TECHNIQUE								
C, ppm	Purity, P	ΔP	Sum F demand, m^3/h	Sum F source, m^3/h	Total F, m^3/h	Cum water flowrate, m^3/h	Water surplus, m^3/h	Cum water surplus, m^3/h
						FDI = 0		
0	1.000000			1.7270	1.7270			
		0.000006				1.727000	0.000011	
6.40	0.999994			1.1100	1.1100			0.000011
		0.000005				2.837000	0.000015	
11.52	0.999988			0.3600	0.3600			0.000026
		0.000001				3.197000	0.000004	
12.80	0.999987			0.5400	0.5400			0.000030
		0.000003				3.737000	0.000012	
16.00	0.999984			0.1100	0.1100			0.000042
		0.000003				3.847000	0.000012	
19.20	0.999981			0.7760	0.7760			0.000054
		0.000011				4.623000	0.000050	
30.00	0.999970			F_{FW} = 5.797	5.7970			0.000104
		0.000010				10.420000	0.000104	
40.00	0.999960			0.1500	0.1500			0.000208
		0.000008				10.570000	0.000085	
48.00	0.999952			0.1690	0.1690			0.000293
		0.000001				10.739000	0.000007	
48.64	0.999951			0.8400	0.8400			0.000300
		0.000003				11.579000	0.000039	
52.00	0.999948		–6.5280	0.0381	–6.4899			0.000338
		0.000008				5.089100	0.000041	
60.00	0.999940			0.0100	0.0100			0.000379
		0.000010				5.099100	0.000053	
70.40	0.999930			1.1530	1.1530			0.000432
		0.000030				6.252100	0.000185	
100.00	0.999900		–7.0500		–7.0500			0.000617
		0.000006				–0.797900	–0.000004	
105.60	0.999894			0.5700	0.5700			0.000613
		0.000058				–0.227900	–0.000013	
164.00	0.999836			0.0240	0.0240			0.000599
		0.000764				–0.203900	–0.000156	
928.00	0.999072			0.0810	0.0810			0.000444
		0.003552				–0.122900	–0.000437	
4480.00	0.995520			0.0690	0.0690			0.000007
		0.000128				–0.053900	–0.000007	
4608.00	0.995392			0.0539	0.0539			0.000000
		0.995392				F_{IWT} = 0	0.000000	
								0.000000

Since there were no other demands at 52 ppm, following Heuristic 2, the demands with the next lowest contaminant concentration (100 ppm) were considered next. For MySem, D2, D3 and D6 existed at the same concentration of 100 ppm. D3, which yielded the biggest flowrate reduction, was chosen first, followed by D2 and D6, according to Heuristic 3.

The pollution-abatement system demand (D3) existed at 100 ppm. Initially, the pollution-abatement system demanded 2.73 m^3/h of water (D3) and produced 2.73 m^3/h of IWT (S17). **Table 6** shows five possible options for reducing abatement system demand. Initially, the plant chose Option 3, which prior to MWN approach was predicted to yield the highest savings (**Table 4 column 3**). However, as shown in **Table 6**, Option 3 actually increased the freshwater target by 2.2% to 6.2183 m^3/h, due to the introduction of a recirculation system that produced no wastewater but relied on makeup water demand. Option 3 had also reduced the total amount of wastewater that could potentially be reused, which, in turn, increased the freshwater target. Option 4 in **Table 6** achieved the best overall freshwater and IWT savings. Choosing Option 4 led to new freshwater and IWT targets at 6.0831 m^3/h and 0.0361 m^3/h respectively, with the pinch point maintained at 4,608 ppm (See fourth row, **Figure 7**).

It was also possible to reduce demand D2, which also existed at 100 ppm. D2, which was the cooling tower makeup, had the second highest flowrate reduction. Heat exchange between cooling tower circuit and liquid-nitrogen circuit had potential to reduce D2 to 5.86 m^3/h, and ultimately the water targets to 5.9452 m^3/h freshwater and 0.0382 m^3/h wastewater (see eleventh row of **Figure 7**). The pinch point was maintained at 4,608 ppm.

Demands D6 (wash basin) and D7 (ablution) were reduced to 0.002 m^3/h and 0.035 m^3/h respectively by changing the normal water taps to laminar taps. This also reduced sources S23 and S24. However, when targeted using WCA, the freshwater and wastewater targets increased slightly to 5.9455 m^3/h and 0.0385 m^3/h. Hence, this process change was rejected.

External water sources. The next WMH process change was to add external water source at concentrations lower than the new pinch point concentration of 4,608 ppm. Based on the plant's available roof area and rain distribution, it was possible to harvest 0.11 m^3/h of rainwater with a concentration of 16 ppm as a new water source. This option had potential to reduce the freshwater and wastewater targets to 5.8349 m^3/h and 0.0379 m^3/h, respectively (**Figure 7**). The pinch point remains 4,608 ppm.

Regeneration. Regeneration was the final process change considered according to the WMH. Freshwater savings could only be realized through regeneration above or across the pinch. Regenerating all 'WB201 in-operation' (S9) at 23,360 ppm and 0.0201 m^3/h of 'WB101 in-operation' (S5) at 4,608 ppm to 52 ppm by carbon bed, EDI and ultraviolet (UV) treatment systems reduced the freshwater and wastewater targets to 5.797 m^3/h and 0 m^3/h respectively (**Table 7**). Considering the IWT was excluded from integration, the new IWT flowrate after regen-

rial balances, and isolates the appropriate water sources (outlet streams with potential to be recycled) and water demands (inlet streams representing process water requirements) having potential for integration. Water sources and demands are listed in terms of quantity (flowrate) and quality (contaminant concentration). In a water-intensive process plant, specifying the limiting data is a tricky and time-consuming exercise, and is typically the bottleneck, but more importantly, the critical success factor for a water minimization project. To isolate the relevant limiting data, readers are referred to Reference [26]. Practical steps and rule-of-thumbs for selecting candidate process units for water-saving projects, extracting the right data, preparing a water balance diagram and isolating the candidate water sources and demands are discussed in detail.

Step 2. Determine MWR targets

The second step is to establish the base case MWR targets, typically, the overall freshwater requirement and wastewater generation for the process.

WMH levels	Specific process changes considered	New FW target, m^3/h	New IWT+WW [based on limiting data] target, m^3/h	New pinch point concentration, ppm	New total IWT (all IWT considered) target, m^3/h
Initial	None	39.94	34.85	22360	34.4500
Reuse	Base case (MWR)	11.0400	0.0190	22360	5.7090
+ Elimination	Eliminate WB cooling 202 (D13) and 203 (D12)	8.3525	0.0215	22360	3.0215
+ Reduction	WB reduction in Plant 1 and Plant 2	6.7518	0.0258	4608	1.4216
	Heater WB201 reduction	6.7314	0.0264	4608	1.3109
	Plant 1 return reduction	6.6094	0.0354	4608	1.3109
	Option 1: EDI decommissioning	6.3038	0.0378	4608	1.0112
	Increase RO rate of recovery	6.2110	0.0380	4608	0.9132
	Reduce multimedia filter backwash and rinsing time	6.0857	0.0387	4608	0.7879
	Option 4: Reduce abatement pollution system (D3 = 0.57 m^3/h and S17 = 0.57m^3/h)	6.0831	0.0361	4608	0.7853
	Cooling tower reduction (D2 = 5.86 m3/h)	5.9452	0.0382	4608	0.7874
+ Outsourcing	Add a source S25=0.11 m^3/h of C = 16 ppm by harvesting rainwater	5.8349	0.0379	4608	0.7871
+ Regeneration	Regenerate remaining IWT to the maximum flowrate for a source	5.7970	0	4608	0.7492
= Minimum water network (MWN) targets		5.7970	0	4608	0.7492

FIGURE 7. Effects of WMH-guided process changes on MWR targets and pinch location

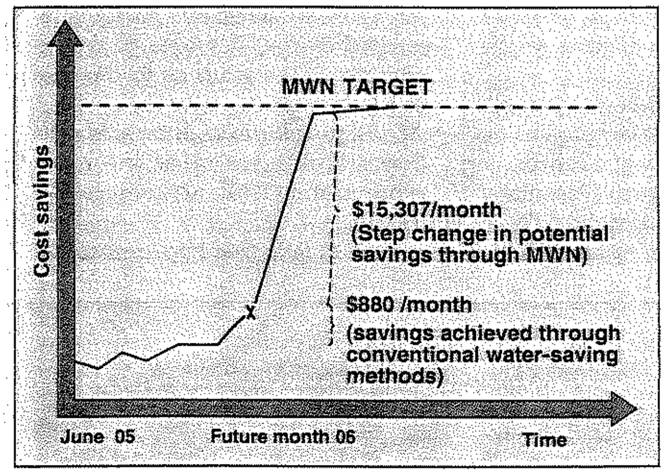

FIGURE 8. Savings achieved compared to savings predicted for MWN

eration was 0.7492 m^3/h. This corresponded to 85.5% freshwater and 97.8% industrial wastewater reductions. Again, the pinch point was maintained at 4,608 ppm.

The minimum water targets were ultimately obtained after considering all options for process changes according to the WMH. Note that targeting the maximum water recovery only through reuse and regeneration resulted in savings of up to 72.4% freshwater and 83.4% wastewater for MySem. Instead, following the holistic framework guided by the WMH enabled potential fresh water and wastewater reductions of up to 85.5% and 97.8% respectively, toward achieving the MWN design. Once the benchmark target was achieved, the minimum water network was designed using various network design approaches such as source-sink mapping diagram [9], nearest neighbor algorithm [11] and mathematical modeling [8, 12–19].

Using MWN targets as benchmark reference

Implementation of the MWN yielded the best achievable benchmark targets for a freshwater flowrate of 5.797 m^3/h and a IWT flowrate of 0.7492 m^3/h, reducing freshwater 85.5% and IWT 97.8%, and achieving the plant's best performance benchmarks (**Figure 8**). By comparison, application of total reuse using only the WPA method yielded a lower water-savings potentials of 72.4% freshwater and 83.4% wastewater reduction with a 0.59 year payback period [31]. The following month's water bills showed that all the conventional water-reduction strategies applied by the fab only reduced fresh water usage from 42.6 m^3/h to 40.24 m^3/h representing a savings of $880 per month.

An estimated total savings of $194,242 per year was predicted with the implementation of MWN method. A preliminary cost estimate indicated that this best performance required an investment of approximately $75,018 with a payback period of 0.39 years. Note that the schemes proposed and listed in **Figure 7** could also be gradually implemented as part of the company's longer-term utility savings program in line with its quality management practices.

Once the best performance benchmark was established through the MWN method, the predicted maximum savings was then compared with the international benchmark. The International Technology Roadmap for Semiconductor (ITRS 2001) had aimed to reduce high-purity water (HPW) consumption from the current rate of 6–8 m^3 in 2005 to 4–6 m^3 per wafer by 2007 [32]. After cost-effective MWN analysis, MySem had potential to use 4.06 m^3 of DI water per wafer for Fab 1 and 13.73 m^3 of DI water per wafer from Fab 2, down from its previous consumption of 6.3 and 72.4 m^3 of DI water per wafer respectively. Fab 1 has potential to meet the ITRS 2001 target. Fab 2, however, is far from this ITRS target due to its wafer production rate of well below the design capacity.

Target achievement

The MWN technique can help a company realize its best achievable water-savings target and assess its true potential for continuous improvement to fulfill its quality management requirement. Application of MWN technique in a semiconductor plant has shown that savings of up to 85.5 % freshwater and 97.8% industrial wastewater are achievable with an estimated payback period of 4.6 months. The proposed improvement schemes and targets provided useful guidelines for short- and long-term water-saving programs that are generally applicable to any plant. Various approaches for benchmarking such as MWR based on pinch analysis techniques that take into consideration plant design and thermodynamic constraints could also help a company realize its potential for conservation of water as well other resources, such as material and utility heat, power and gases. ❑

Base-case MWR targets exclude other levels of WMH, except reuse and recycling of available water sources and mixing of water sources with freshwater to satisfy water demands.

Established graphical and numerical techniques for setting the MWR targets are widely available. Some popular ones — such as the concentration composite curve (graphical approach [*1, 26*]), concentration interval table for mass exchange network (numerical approach [*27*]) and mass problem table (numerical approach [*7*]) — are ideal for fixed flowrate cases, where water-using processes are modeled as mass-transfer based operations involving water as a lean stream or a mass-separating agent (MSA). For an industrial project where flowrate gains and losses are quite common, it may be necessary to analyze these streams separately and modify the stream data if the fixed-flowrate approach is used [*26*]. A resilient tool should be able to handle both mass-transfer and non-mass- transfer-based water using-operations that involve flowrate gain or losses, such as water used as a solvent or withdrawn as a product or a byproduct of a chemical reaction, or utilized as heating or cooling media. Water-cascade analysis (WCA), which fits the latter category, is used in this work [*5*].

Step 3. Screen process changes

Flowrates and concentrations of water sources and demands can be changed to reduce MWR targets and ultimately achieve the MWN benchmark by observing the basic pinch rules for process changes and prioritizing and assessing all possible process changes options according to the WMH. The fundamental rules to change a process depend on the location of water sources and demands relative to the pinch point of a system:

- ***Above the pinch.*** Beneficial changes can be achieved by either increasing the flowrate or purity of a source, or by decreasing the flowrate or purity requirements of a demand. These changes will increase water surplus above the pinch thereby reducing the amount of freshwater required.
- ***Below the pinch.*** There is already a surplus of water below the pinch; hence any flowrate change made there will not affect the target. An exception to this rule of thumb is for a case where source purity is increased so that it moves to the region above the pinch as in the case of regeneration.
- ***At the pinch point.*** Increasing the flowrate of a source at the pinch concentration will not reduce the targets.

It is vital to note that implementation

NOMENCLATURE

Acronyms

AHU	Air-handling units
BOD	Biological oxygen demand
COD	Chemical oxygen demand
DI	Deionized water
EDI	Electrode ionization
Fab	Fabrication plant
HF	Hydrogen fluoride
IPA	Isopropyl butanol
IWT	Industrial wastewater treatment
MAU	Makeup air units
MMF	Multimedia filter
MWN	Minimum water network
MWR	Maximum water recovery
RO	Reverse osmosis
UV	Ultraviolet
TDS	Total dissolved solids
TSS	Total suspended solids
UF	Ultrafiltration
UPW	Ultrapure water
WB	Wet bench
WCA	Water cascade analysis
WMH	Water management hierarchy
WPA	Water pinch analysis

Symbols

C	Concentration
F	Flowrate

Subscripts

DI	Deionized water
FW	Freshwater
IWT	Industrial wastewater treatment

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